



WDM Pumping and highly nonlinear fibers for Raman amplification

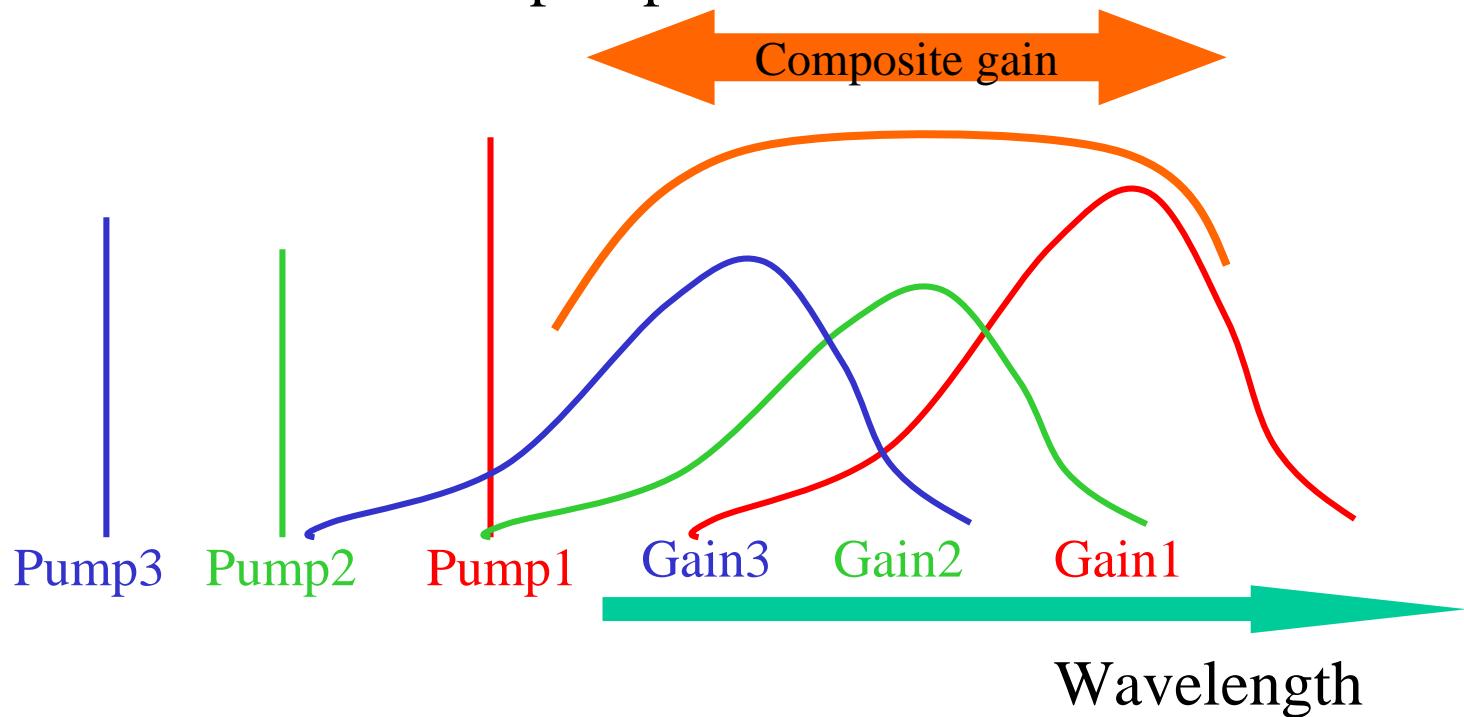
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Outline

- Review of the state-of-the-art WDM Pumping scheme
 - Flattening gain and noise
 - Technology evolution of pump laser diodes
- Optical pulse source using highly nonlinear fibers
 - Germano-Silicate highly nonlinear fibers (HNLF)
 - Structure and performance
 - Comparisons with other technologies
 - High repetition-rate optical pulse source
 - Simple scheme using CDPF and dual frequency CW source
 - Duration tuning using Raman amplified adiabatic soliton compression

WDM Pumping

- Simultaneously launch pumps at different wavelengths
- Realize a broad and flat composite gain
- Typically use FBG stabilized pump lasers



K. Rottwitt and H. Kidorf, OFCPD98

S. Namiki, JSTQE, p. 3, 2001

Superposition rule and contributed gain of WDM pumping

- Single frequency pumping

$$\frac{dI_s(z)}{dz} = g_R(\nu_p, \nu_s) I_p(z) I_s(z) - \alpha I_s$$

- WDM pumping

$$\frac{dI_s(z)}{dz} = \sum_i g_R(\nu_{p,i}, \nu_s) I_{p,i}(z) I_s(z) - \alpha I_s$$

$$G_{lin.} = e^{\sum_i^L g_R(\nu_{p,i}, \nu_s) \int_0^L I_{p,i}(z) dz}$$

$$G_{dB} \propto \sum_i g_R(\nu_{p,i}, \nu_s) \overline{I_{p,i}(z)} L$$

$$\equiv \sum_i C_i g_R(\nu_{p,i}, \nu_s)$$

Contributed gain factor

$I_s(z)$: signal level

$I_p(z)$: pump level

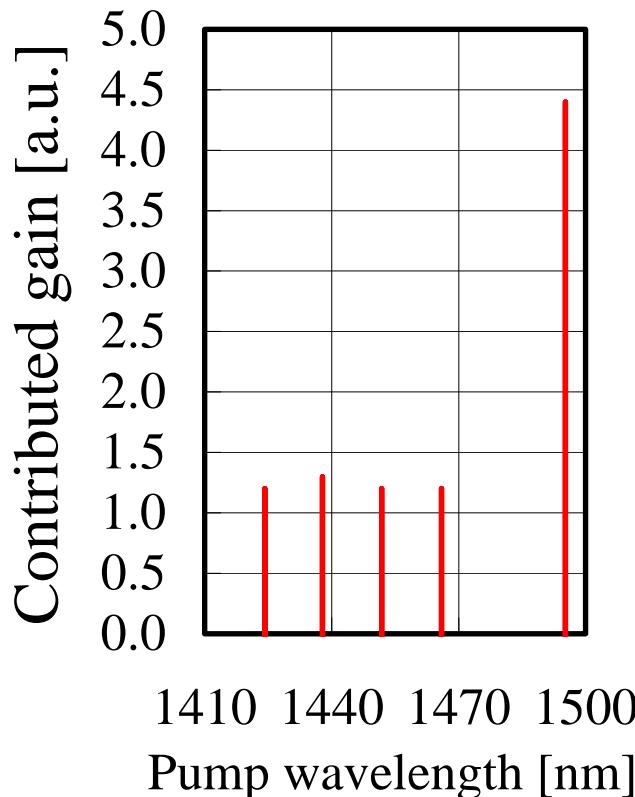
$g_R(\nu_p, \nu_s)$: Raman gain efficiency

α : attenuation coefficient

WDM pumping: Flattening composite Raman gain

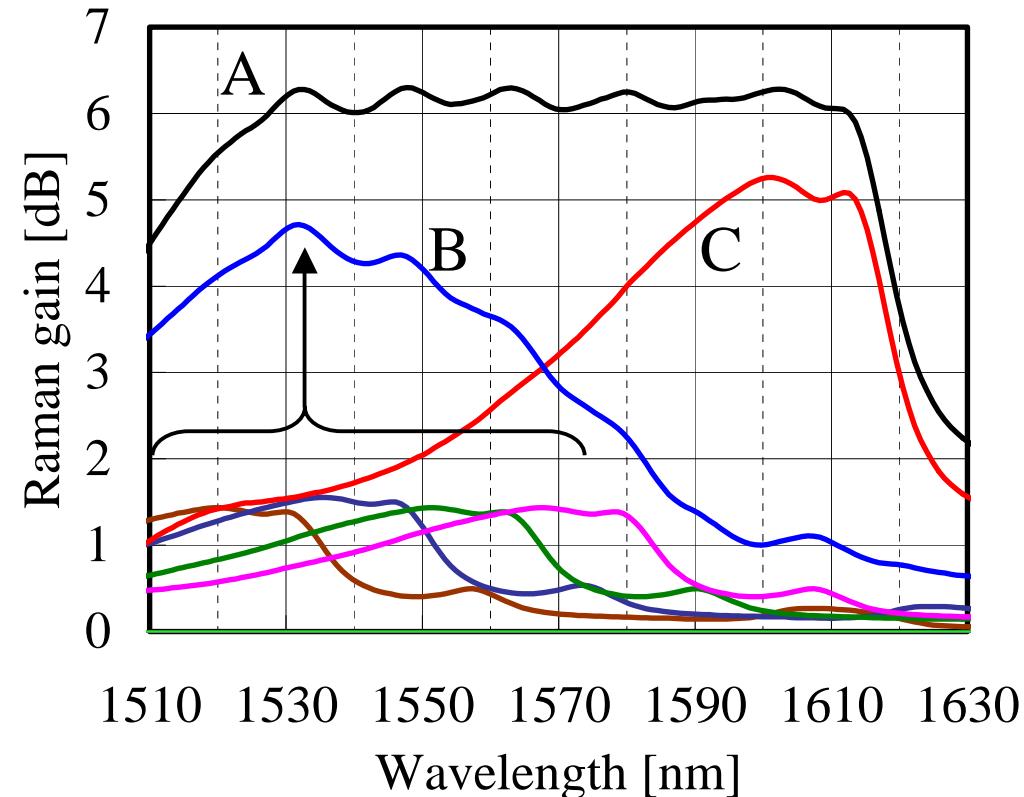
Design parameters:

- wavelength allocation
- contributed gain allocation

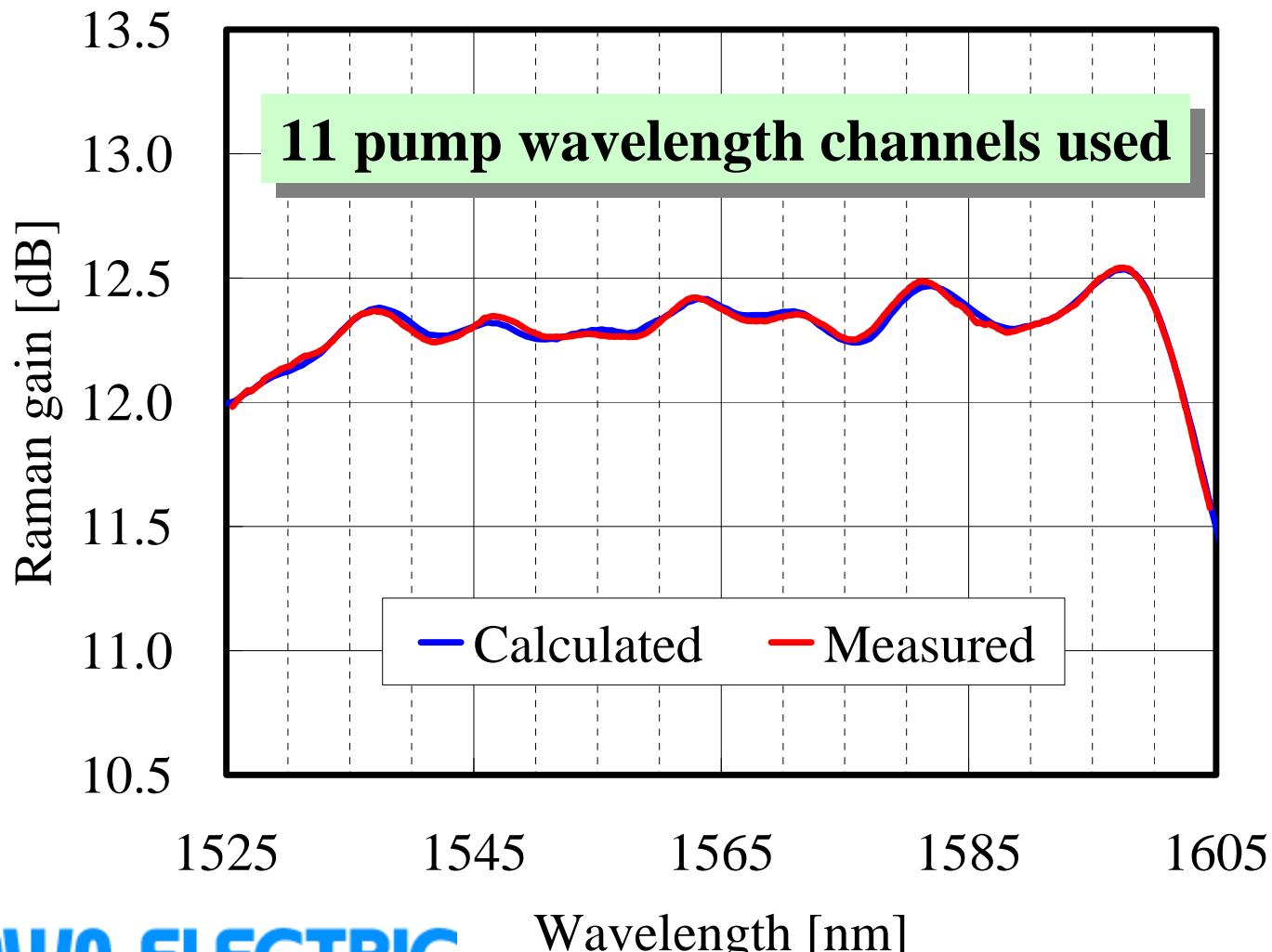


Specifications:

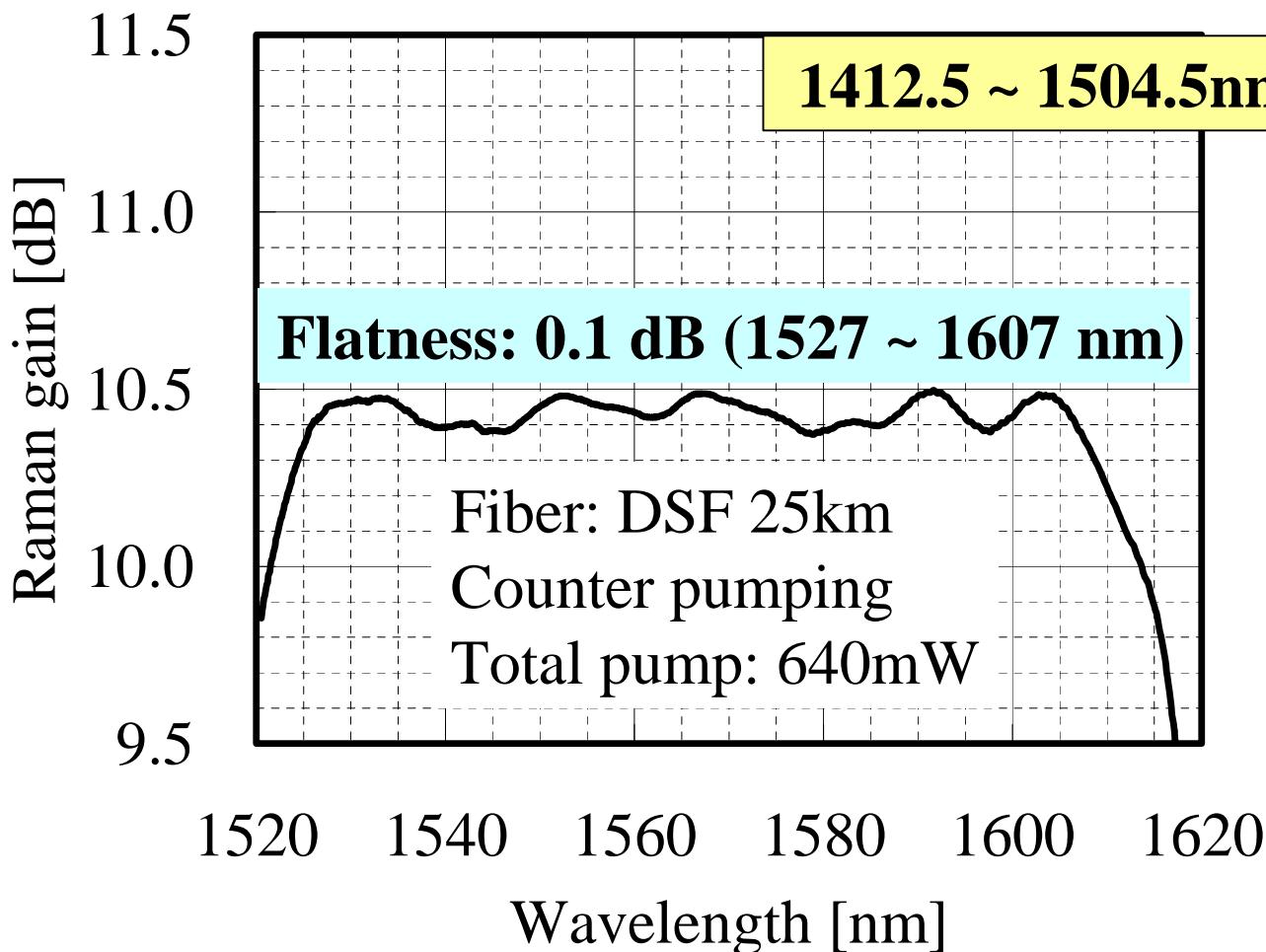
- fiber type, gain and flatness
- bandwidth, number of LDs



Experimental verification of superposition rule

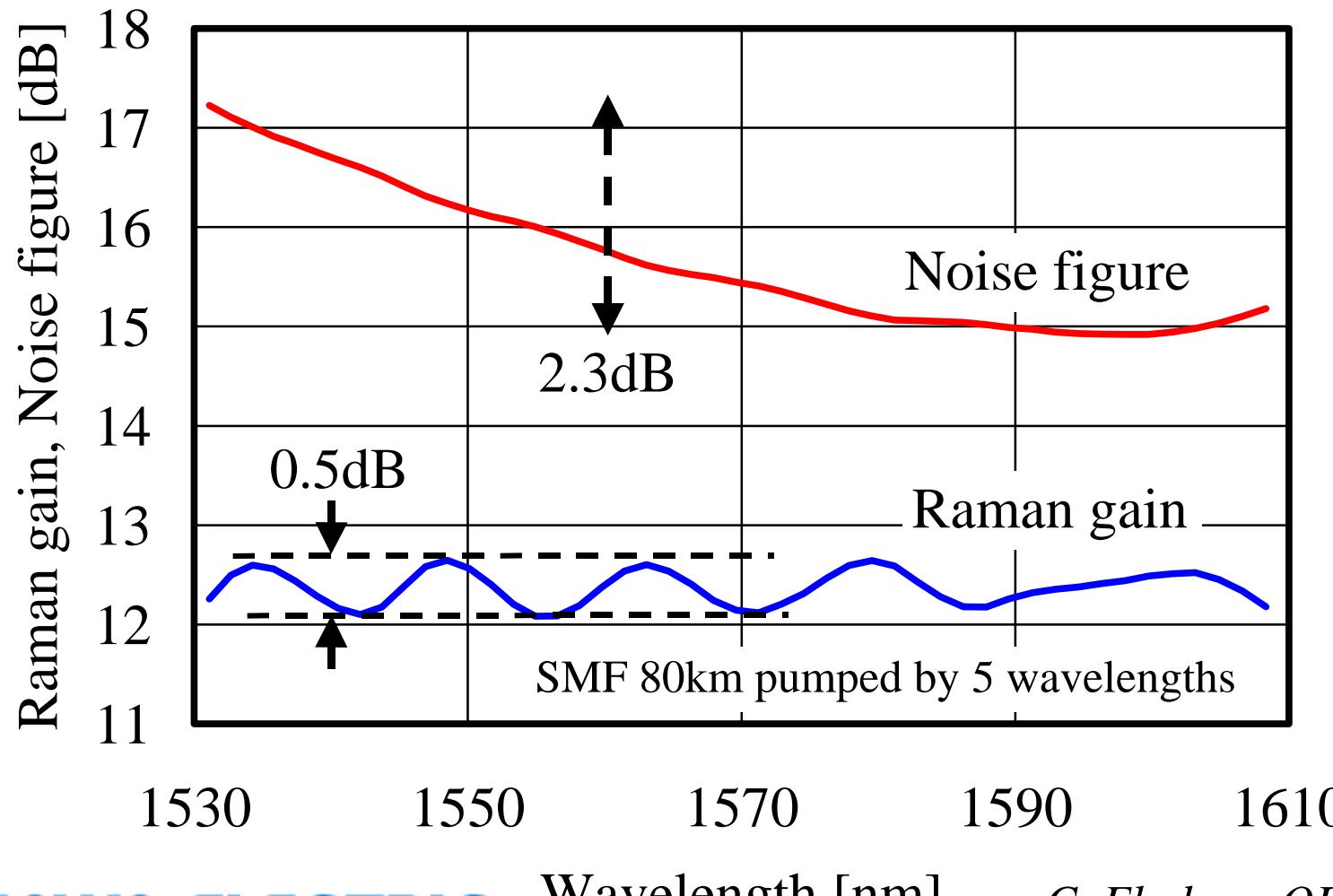


Example : Ultraflat broadband amplifier 1-THz grid 12 channel WDM pumping source

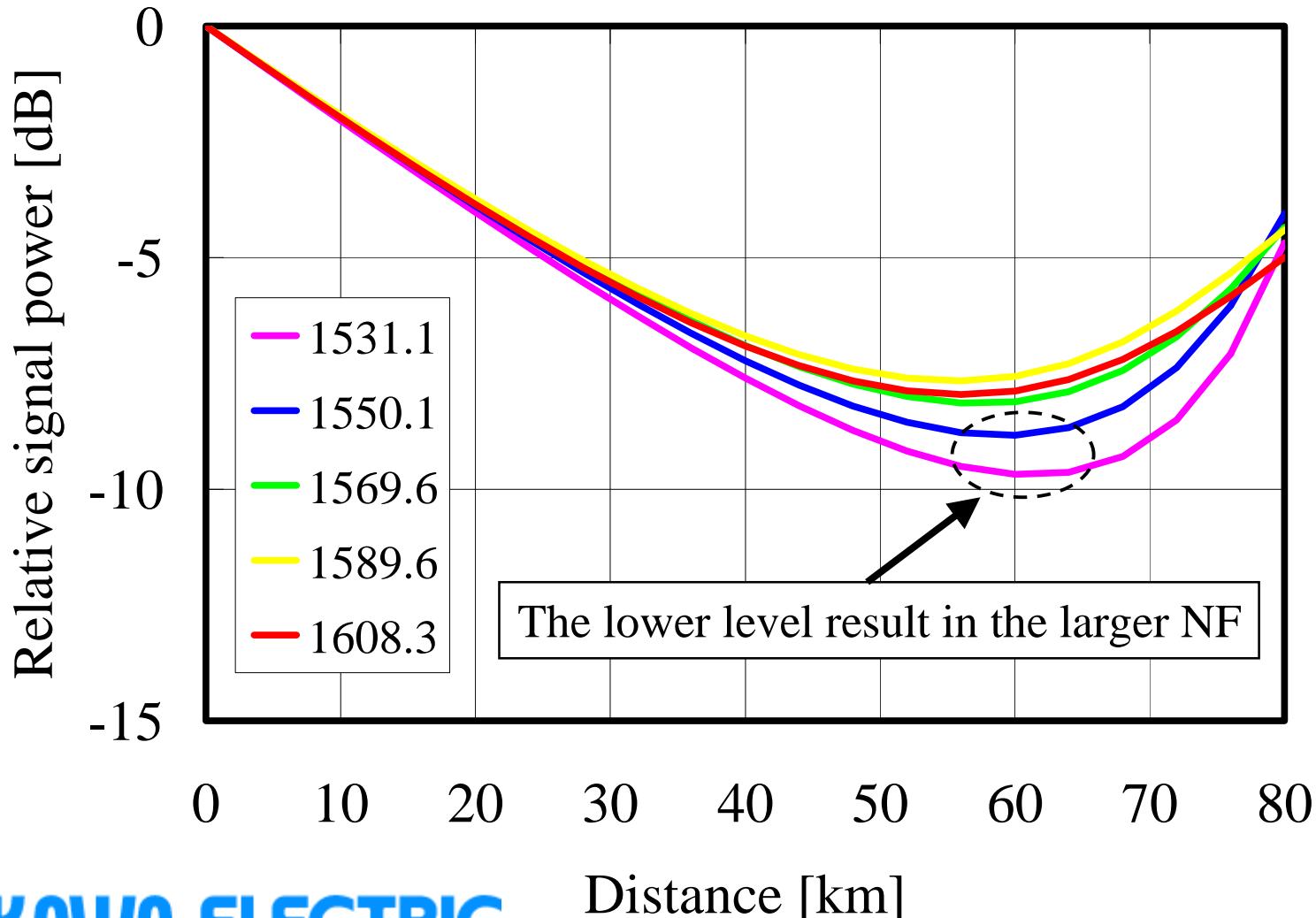


Pump frequency [THz]	Launched power [mW]
212.2	91
211.1	98
210.2	95
209.2	52
208.2	52
207.3	39
206.2	38
205.3	29
204.2	35
203.3	33
200.1	51
199.3	32

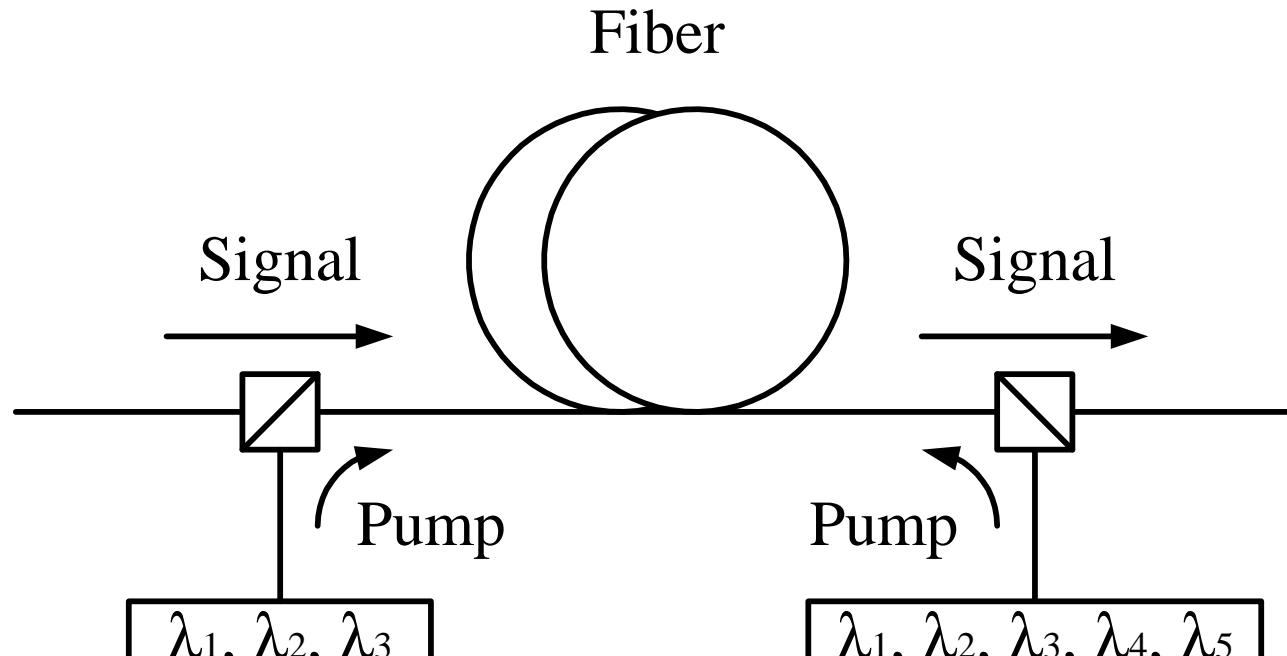
ASE Noise figure spectrum in counter-pumped broadband Raman amplifier



Origin of wavelength dependence of NF



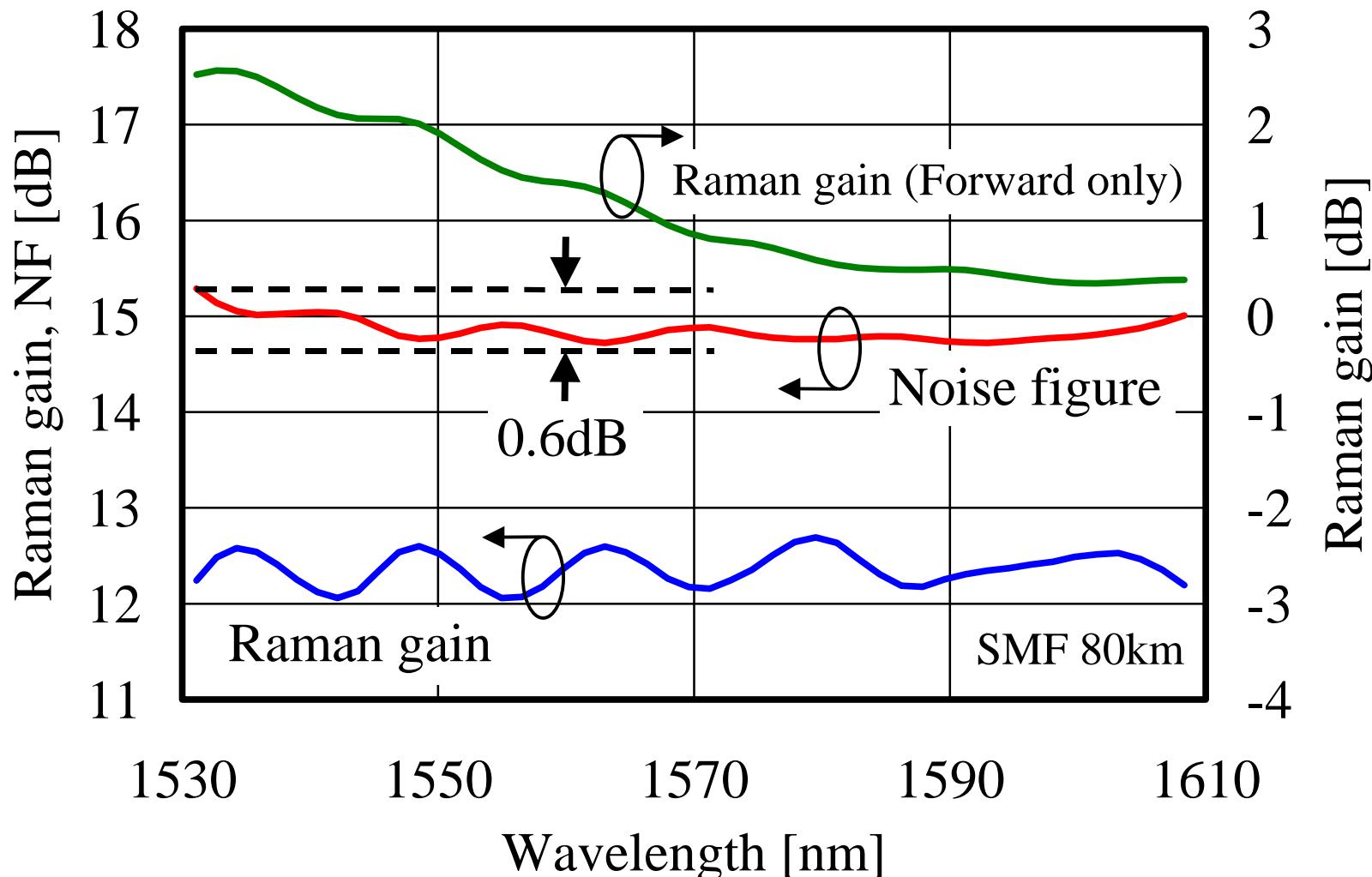
Flattening ASE noise figure spectrum



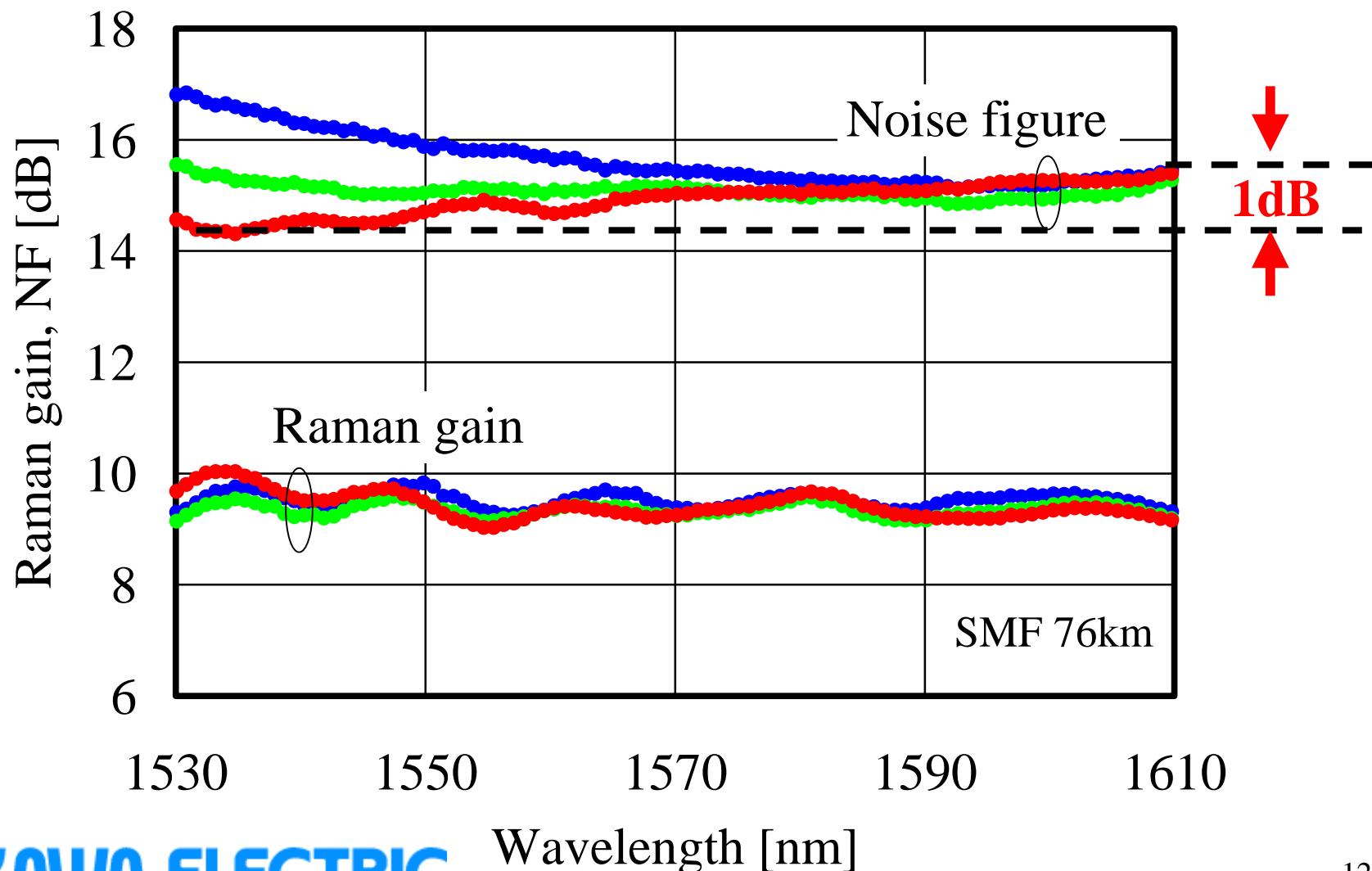
The shorter three wavelengths
are used for noise-flattening

These five wavelengths are
necessary for gain-flattening

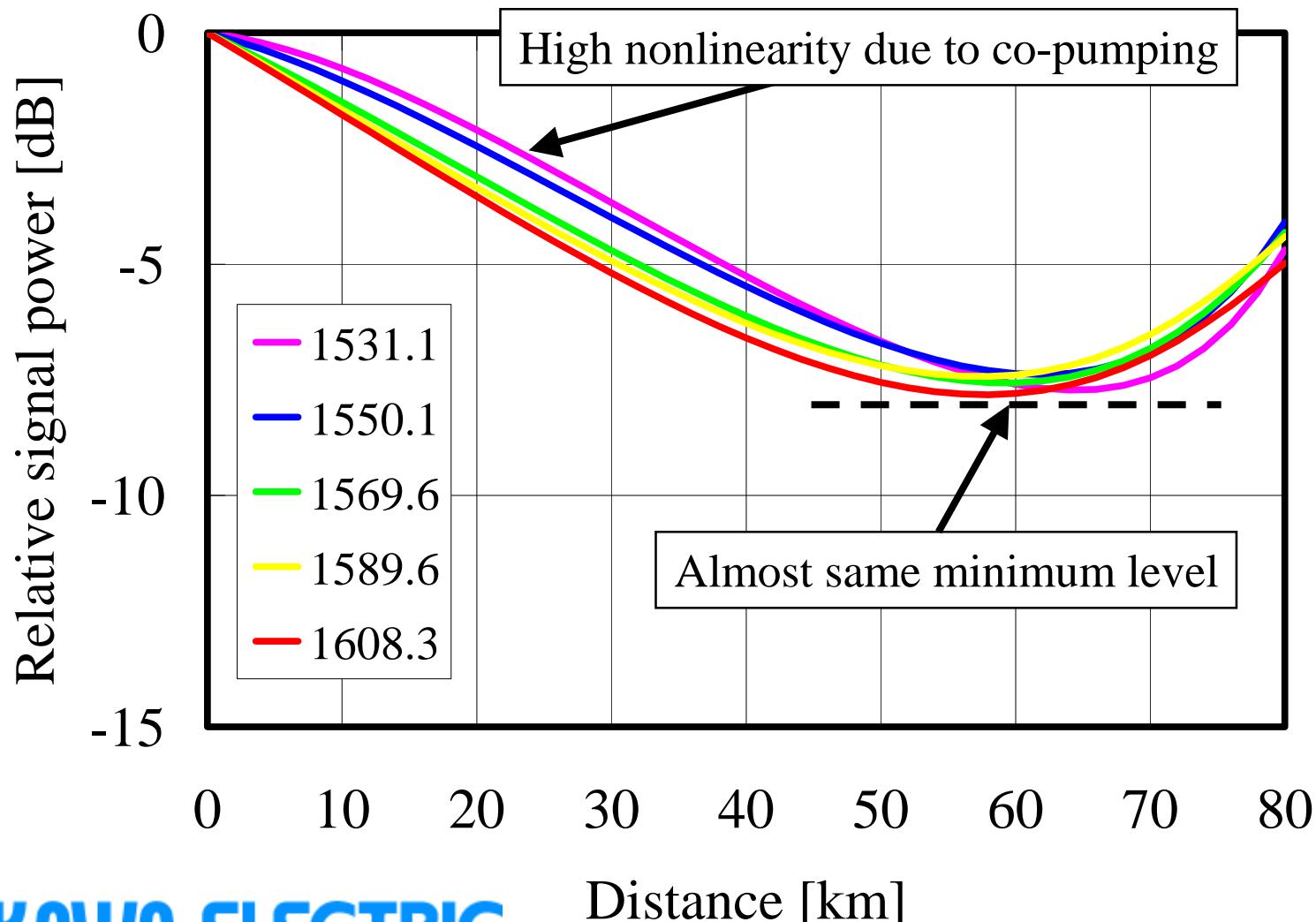
Simulation result of bi-directional pumping for noise-flattening



Experimental result of NF spectrum control



Signal excursion in bi-directional pumped Raman amplifier



System design: Flattening overall characteristics

- Signal level including SRS tilt
- *Gain*
- *ASE noise figure*
- Double Rayleigh backscattering noise
- Nonlinear phase shift



These items could be flattened by realizing a uniform level excursion over the signal range,

If...

- Attenuation and Rayleigh coefficients
- Thermal noise ...



these were flat!!

Optimize the balance!

Don't forget about Pump FWM issues!

An established modeling for multi-wavelength

$$\frac{dP_v^{\pm}}{dz} = -\alpha_v P_v^{\pm} + \varepsilon_v P_v^{\mp}$$

$$+ P_v^{\pm} \sum_{\mu > v} \frac{g_{\mu v}}{A_{\mu}} (P_{\mu}^{+} + P_{\mu}^{-})$$

$$+ 2h\nu\Delta\nu \sum_{\mu > v} \frac{g_{\mu v}}{A_{\mu}} (P_{\mu}^{+} + P_{\mu}^{-}) \left[1 + \frac{1}{\exp\left[\frac{h(\mu-v)}{kT}\right] - 1} \right]$$

$$- P_v^{\pm} \sum_{\mu < v} \frac{\nu}{\mu} \frac{g_{\nu\mu}}{A_{\nu}} (P_{\mu}^{+} + P_{\mu}^{-})$$

$$- 4h\nu P_v^{\pm} \sum_{\mu < v} \frac{g_{\nu\mu}}{A_{\nu}} \left[1 + \frac{1}{\exp\left[\frac{h(\nu-\mu)}{kT}\right] - 1} \right] \Delta\mu$$

- Fiber loss and Rayleigh back-scattering

- Raman gain due to shorter wavelength

- ASE noise with thermal factor

- Pump depletion due to longer wavelength

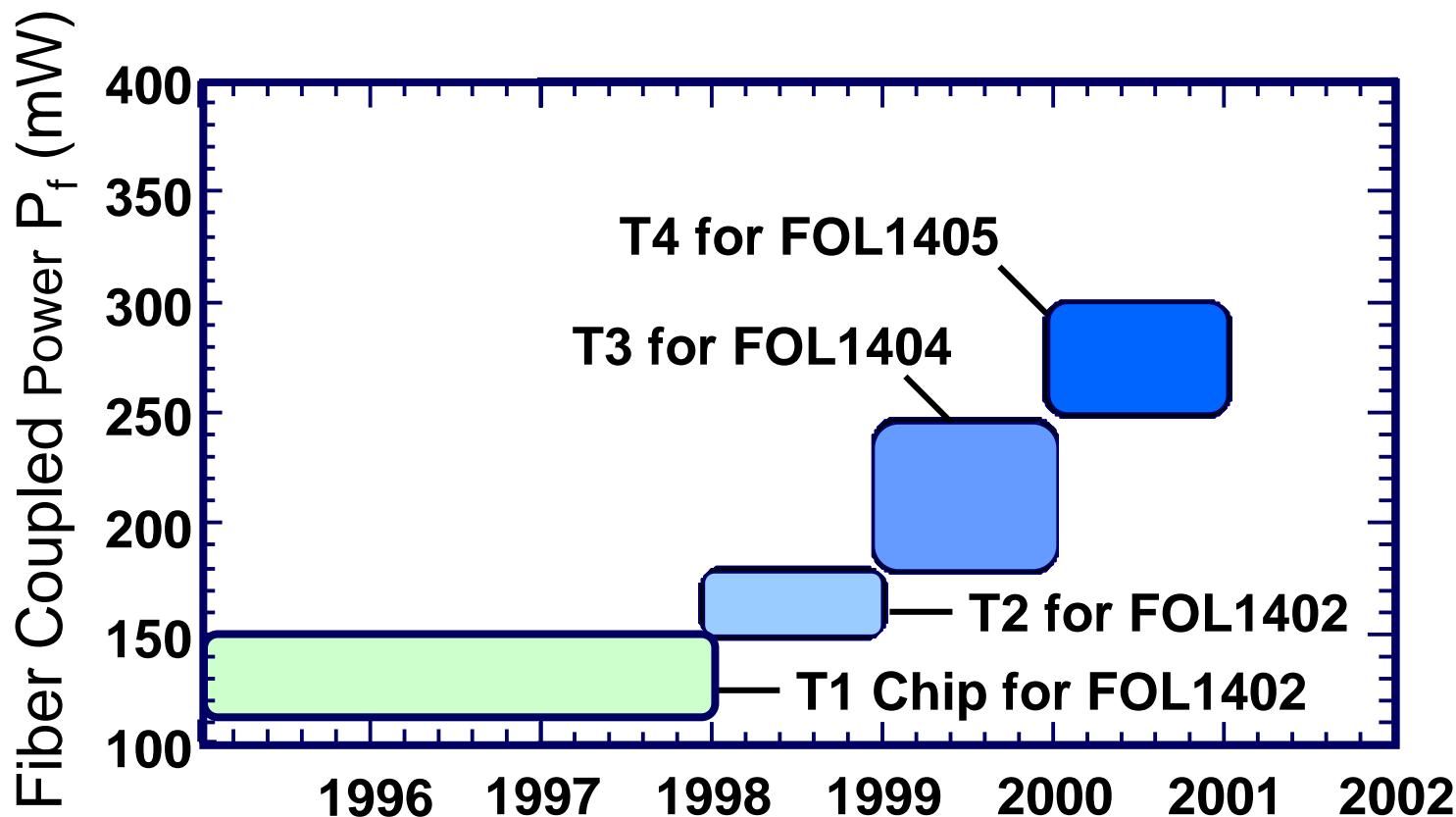
- Loss due to noise emission

Gain coefficient and effective area depend on frequency!!

Technology evolution of pump laser diodes

- Trend for higher power
- Challenge for low noise pump lasers

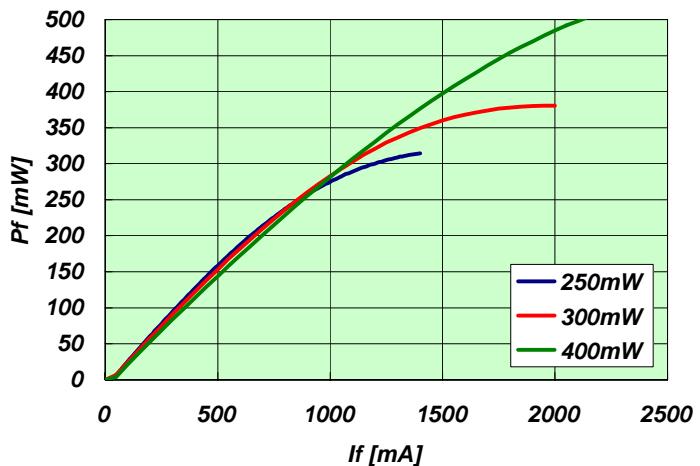
Transition of output power of laser diodes in market



New type of 14xx Laser for high power

Hybrid dual-stripe Pump

Conventional Single stripe



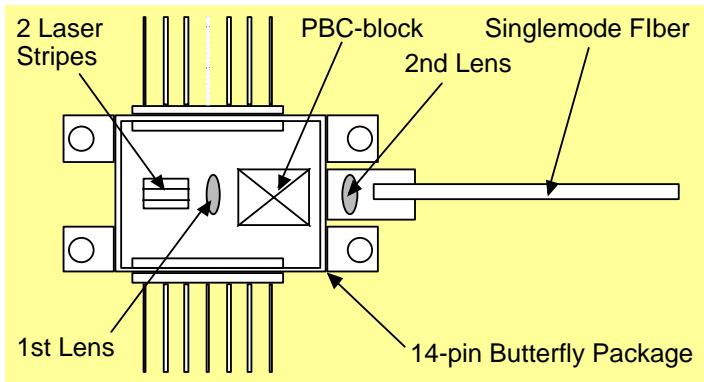
Single stripe



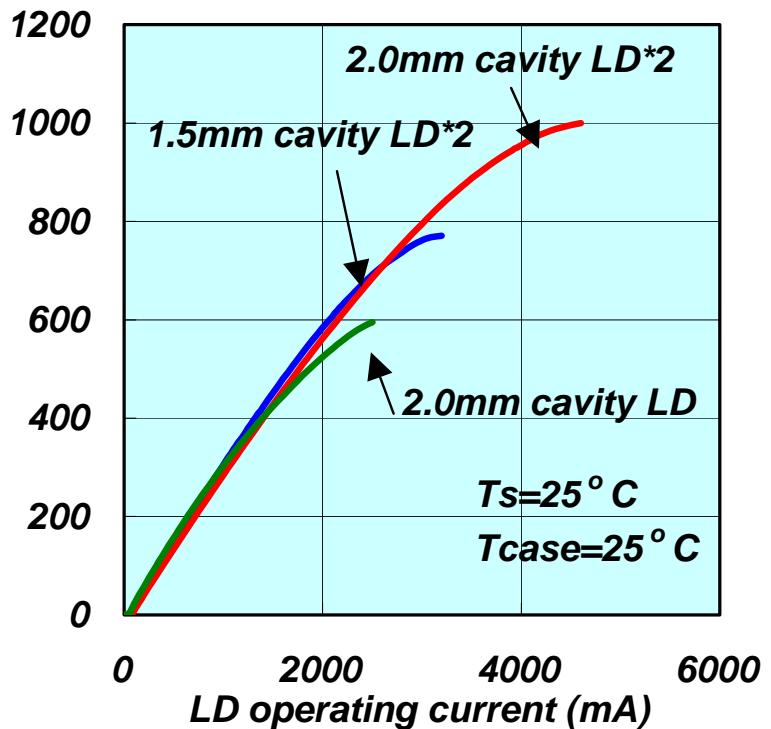
Hybrid dual stripe



Polarization multiplex output



**Fibre coupled power
from one LD module (mW)**



Issues of co-pumping

- Motivations for bi-directional pumping:
 - Essential to flattening the noise figure
 - Smaller signal level-excursions
 - Lower power for the same OSNR improvement compared with counter-pumping
 - Also good for safety
- Concerns: Pump-signal noise transfer
 - RIN
 - Mode partition noise
 - Gain saturation cross talk

Need for low noise pumps

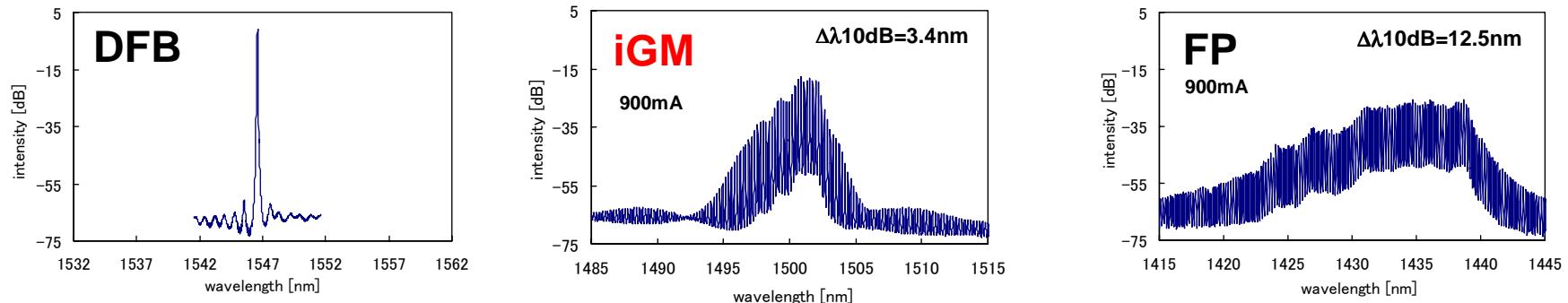
A fundamental trade-off of pump lasers Noise versus SBS suppression

- Broad-linewidth = FBG-stabilized LD
 - No SBS
 - High RIN due to external cavity modes
- Single narrow-linewidth longitudinal mode = DFB-LD
 - Low RIN
 - No Mode Partition Noise
 - High SBS!!
- Many narrow-linewidth longitudinal modes = FP Lasers
 - High RIN at lower frequencies
 - High Mode Partition Noise
 - Low SBS

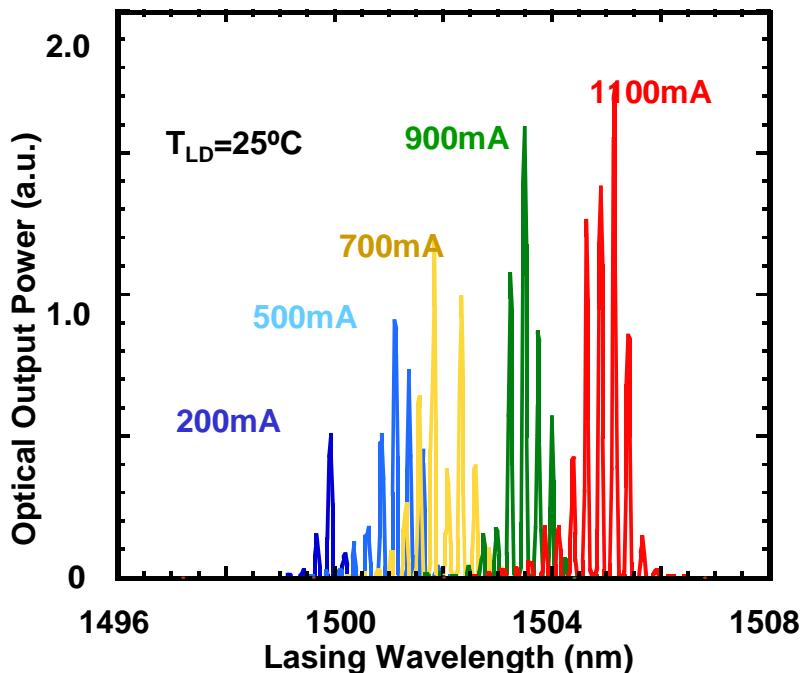
iGM laser optimizes the trade-off!

New type of 14xx Laser for low noise Inner Grating Multi-mode (iGM) Laser

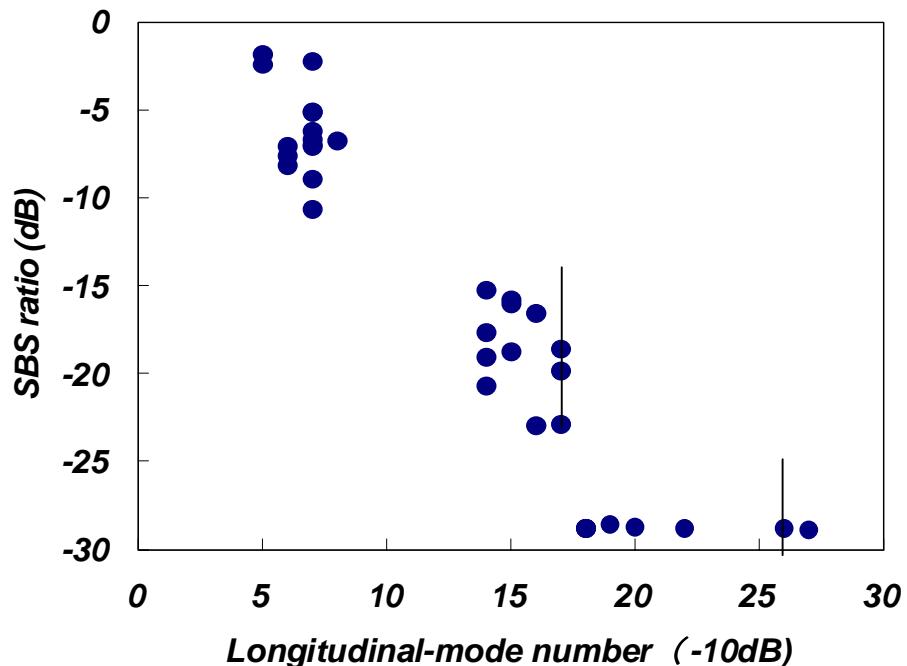
Low noise pumping with SBS suppression



Controlled multimode



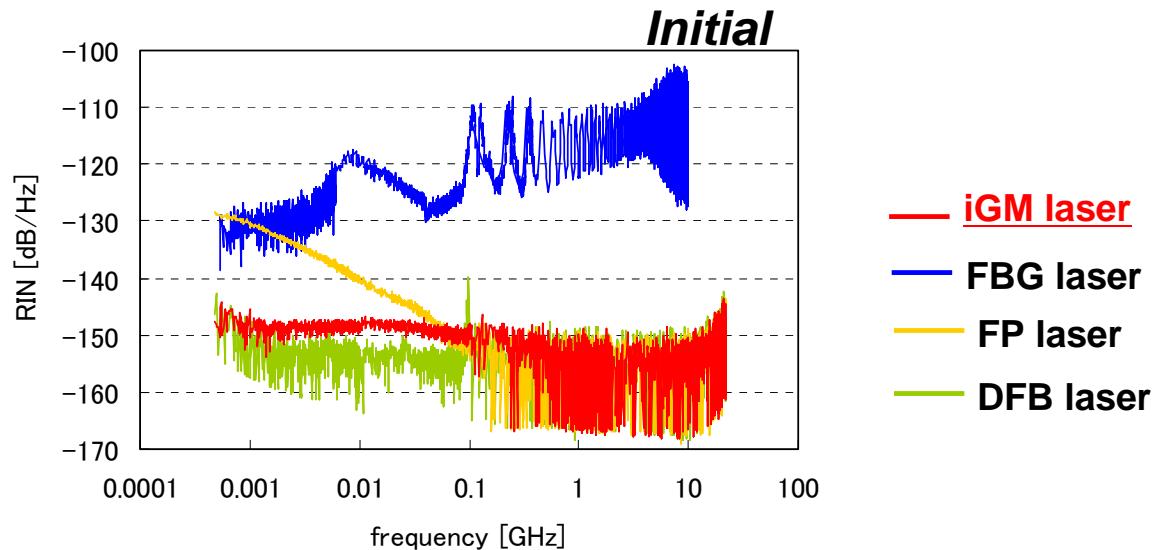
SBS Reduction by Mode design



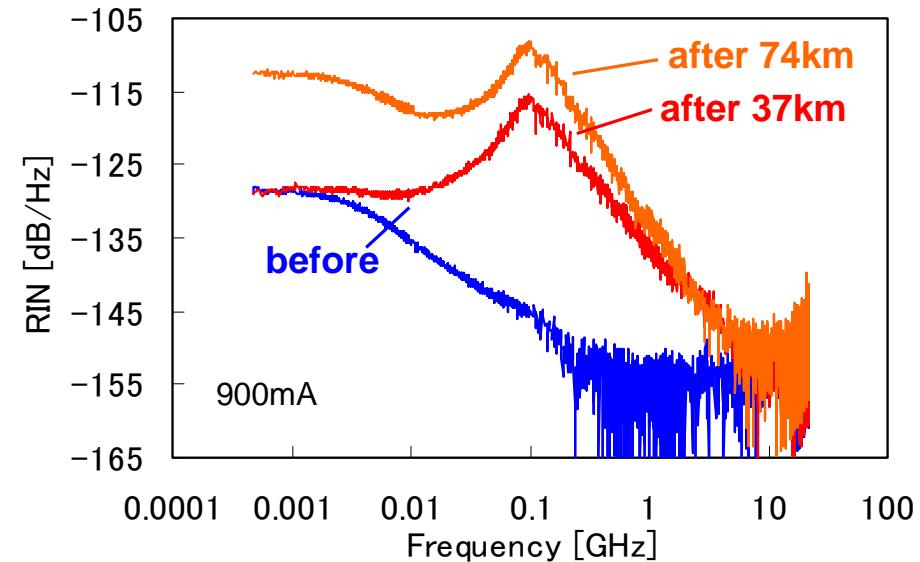
New 14xx Laser

Inner Grating Multi-mode (iGM) Laser

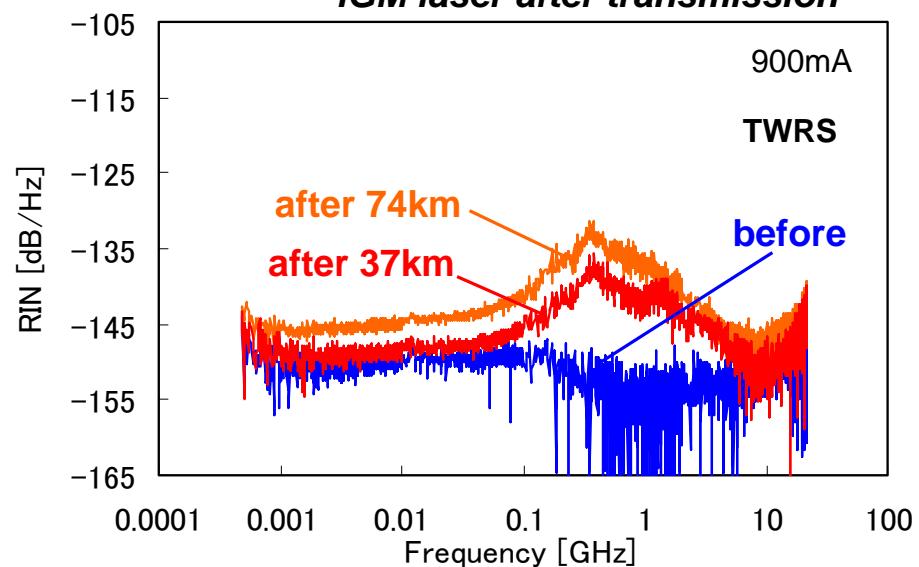
**Excellent RIN and
Mode partition noise with
well suppressed SBS**



FP laser after transmission



iGM laser after transmission



State-of-the-art WDM pumping units



5 wavelength standard unit

Field compatible ultraflat gain 13 wavelength unit

FURUKAWA ELECTRIC

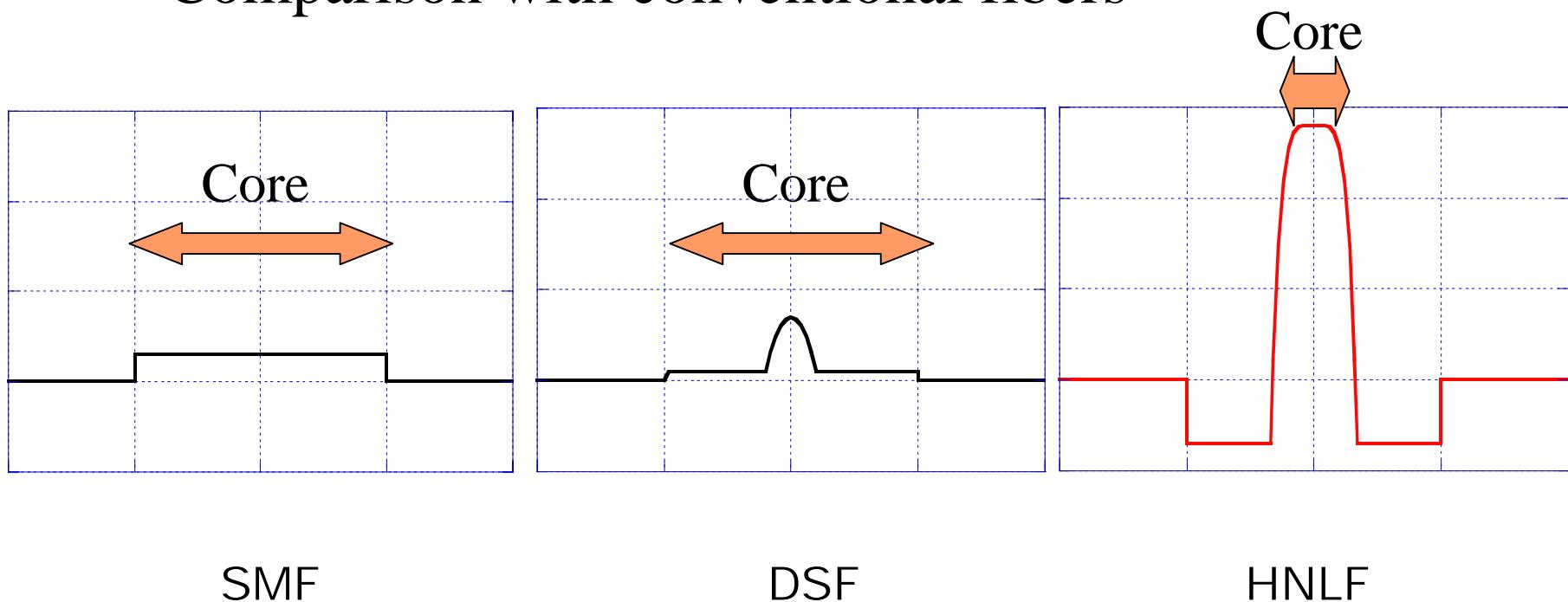
Highly nonlinear optical fibers and high-repetition-rate optical pulse source

Advantages of nonlinearity in optical fiber

- fast response, ($> 10\text{THz}$)
- low noise
- low loss
- wide band operation
- high reliability
- potentially bit rate transparent
- potentially low power consumption w/o complicated electronics

How can we enhance nonlinearity ?

- Comparison with conventional fibers



SMF

DSF

HNLF

$\text{SiO}_2\text{-GeO}_2$ based HNLF

- Preliminary works
 - From the development of low bend loss DSF
 - NTT, S. Sudo, et.al., (1986)
 - apparently described, “for highly nonlinear devices”
 - VAD, $\Delta n=2.9\%$, core diam.= $2.3\mu\text{m}$, 0.82dB/km
 - Cambridge Univ., M. J. Holmes, et.al., (1995),
- 2nd Generation
 - **Furukawa**, (S. Arai, *et.al.*, *OECC*, 1996)
 - CGW (D. A. Pastel, *et.al.*, *OFC*, 1997)
 - Sumitomo (M. Onishi, *et.al.*, *ECOC*, 1997)
 - BT (S. Y. Set, *et.al.*, *OFC*, 1998)
 - **Furukawa** (J. Hiroishi, *et.al.*, *OECC*, *ECOC-PD*, 2002)
- 3rd Generation...?
 - Holey Fiber, Bi-doped HNLF, ...

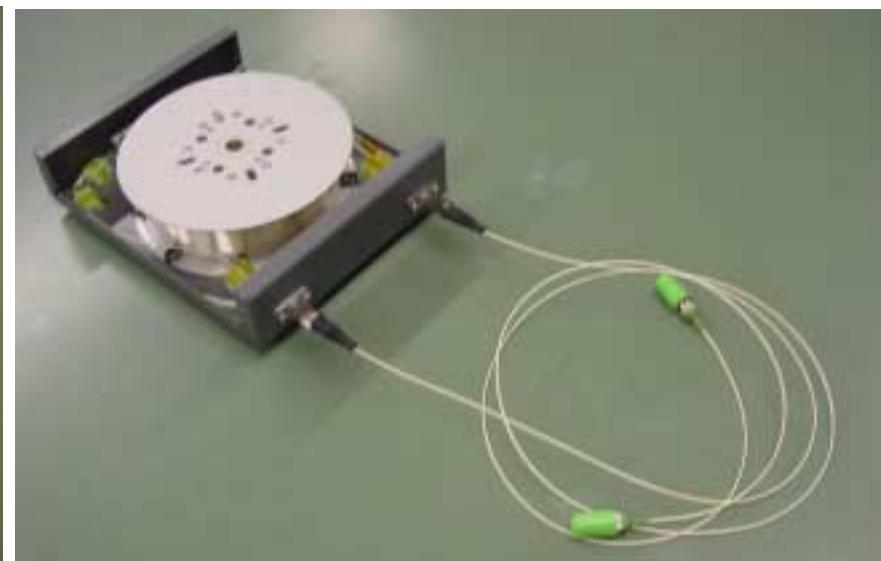
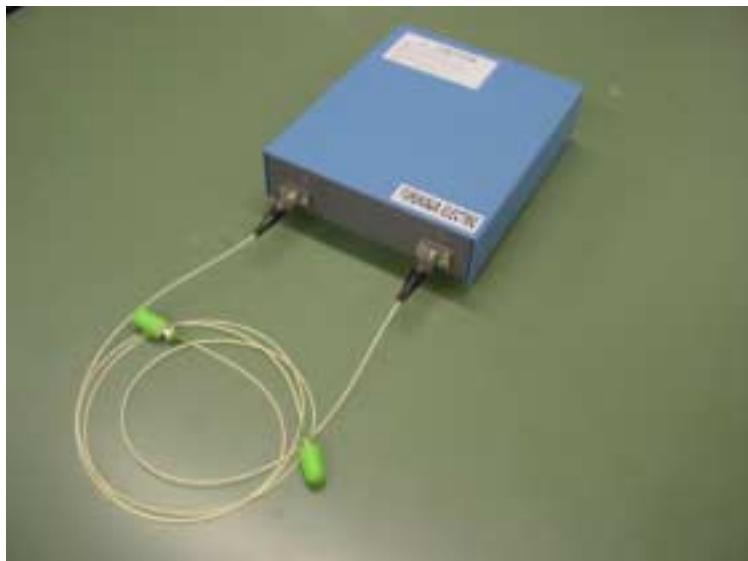
Characteristics

- A comparison

Parameters (@1550nm)	SMF	DSF	HNLF- A	HNLF- B	HNLF-C	HNLF- D
atten. coeff., dB/km	0.20	0.21	0.83	0.37	0.41	1.16
λ_0 , nm	1310	1550			1500-1600	
D -slope ps/nm ² /km	0.09	0.07	0.031	0.022	0.016	0.013
A_{eff} μm^2	80	50	12.0	14.2	14.6	9.7
nonlinearity, $\text{W}^{-1}\text{km}^{-1}$	1.3	2.7	17.5	12.9	12.6	25.1
splicing loss	~ 0 dB		$\lesssim 0.3\text{dB}$			

HNLF module

- Handy module for study of the fiberoptic nonlinear subsystems
 - L180mm × W150mm × H40mm
 - Wound around a 60mm ϕ bobbin
- Almost ready for market

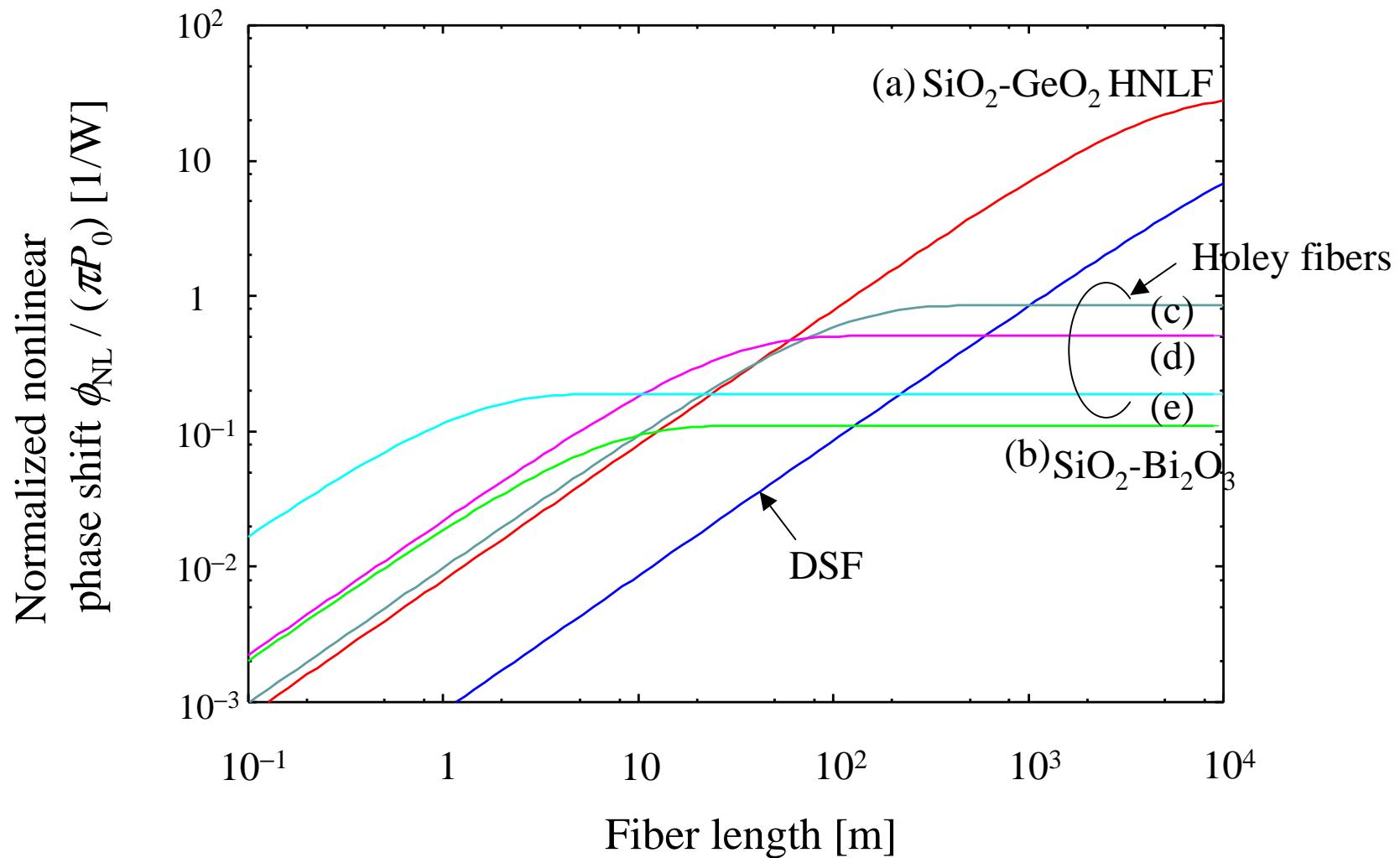


Comparison of different technologies

	$\text{SiO}_2\text{-GeO}_2$	DSF	$\text{SiO}_2\text{-Bi}_2\text{O}_3$	HNL-holey fibers		
	(a)		(b)	(c)	(d)	(e)
$\gamma [\text{km}^{-1}\text{W}^{-1}]$	25	2.7	64.2	31	70	550
$\delta [\text{dB/km}]$	1.16	0.21	800	50	190	4000
$D [\text{ps/nm/km}]$	-0.08	N.A.	-130	100	-30	N.A.

(a) J. Hiroishi et al., ECOC'02, Paper PD1.5 (2002), (b) K. Kikuchi, et al., Electron. Lett., 38, 166 (2002), (c) J. H. Lee et al., ECOC'02, Paper 3.4.3 (2002), (d) W. Belardi et al., ECOC'02, Paper PD1.2 (2002), (e) T. M. Monro, et al., OFC'02 Paper PD FA1 (2002).

Figure of merit of highly nonlinear fiber



- (a) J. Hiroishi et al., ECOC'02, Paper PD1.5 (2002), (b) K. Kikuchi, et al., Electron. Lett., 38, 166 (2002), (c) J. H. Lee et al., ECOC'02, Paper 3.4.3 (2002), (d) W. Belardi et al., ECOC'02, Paper PD1.2 (2002), (e) T. M. Monro, et al., OFC'02 Paper PD FA1 (2002).



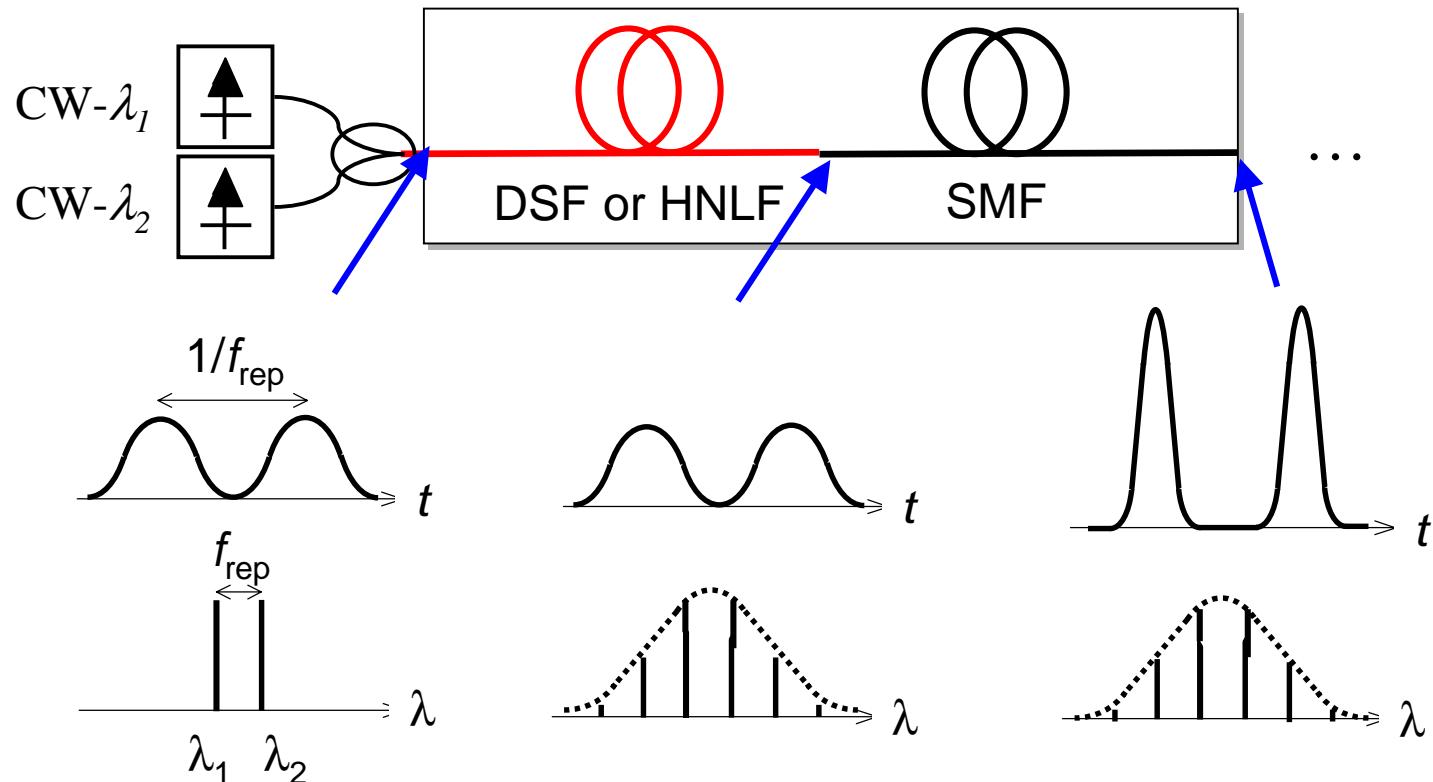
An application : High-Repetition Rate Optical Short Pulse

CDPF, comb-like dispersion profiled fiber

E. M. Dianov, et.al., *Opt. Lett.*, 1989, p. 1008.

S. V. Chernikov, J. R. Taylor & R. Kasyap, *Electron. Lett.*, 1994, p. 433.

- Principle
 - Repetition rate = frequency interval of two-CW sources
 - Repeating the nonlinear chirp and its compensation with GVD



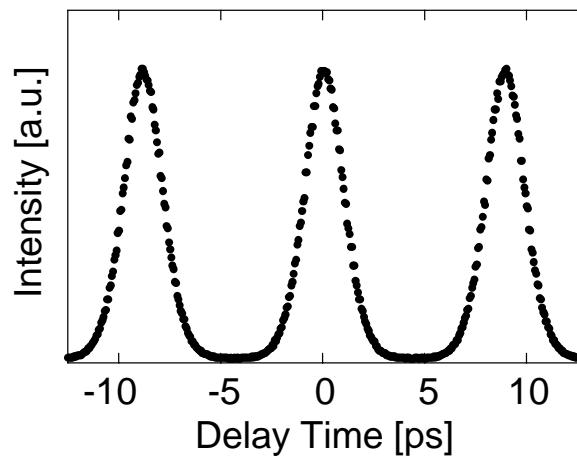
Results using HNLF in CDPF

- Repetition rate = 133 GHz, stable in long time

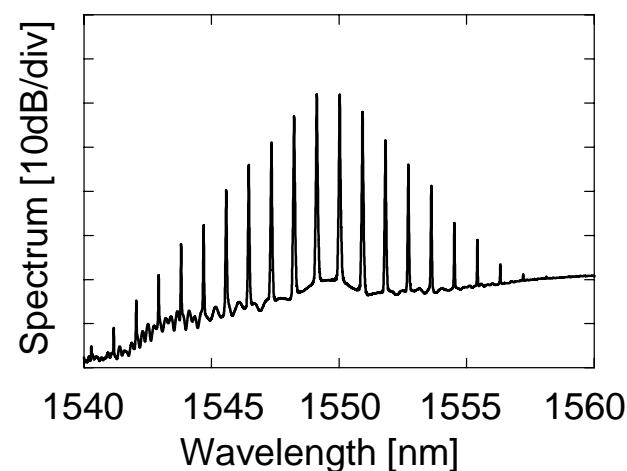
- by using 5-pair CDPF (Total < 1 km long)

- Less than 20 dB launched beat signal power

▼ Autocorrelation trace



▼ optical spectrum



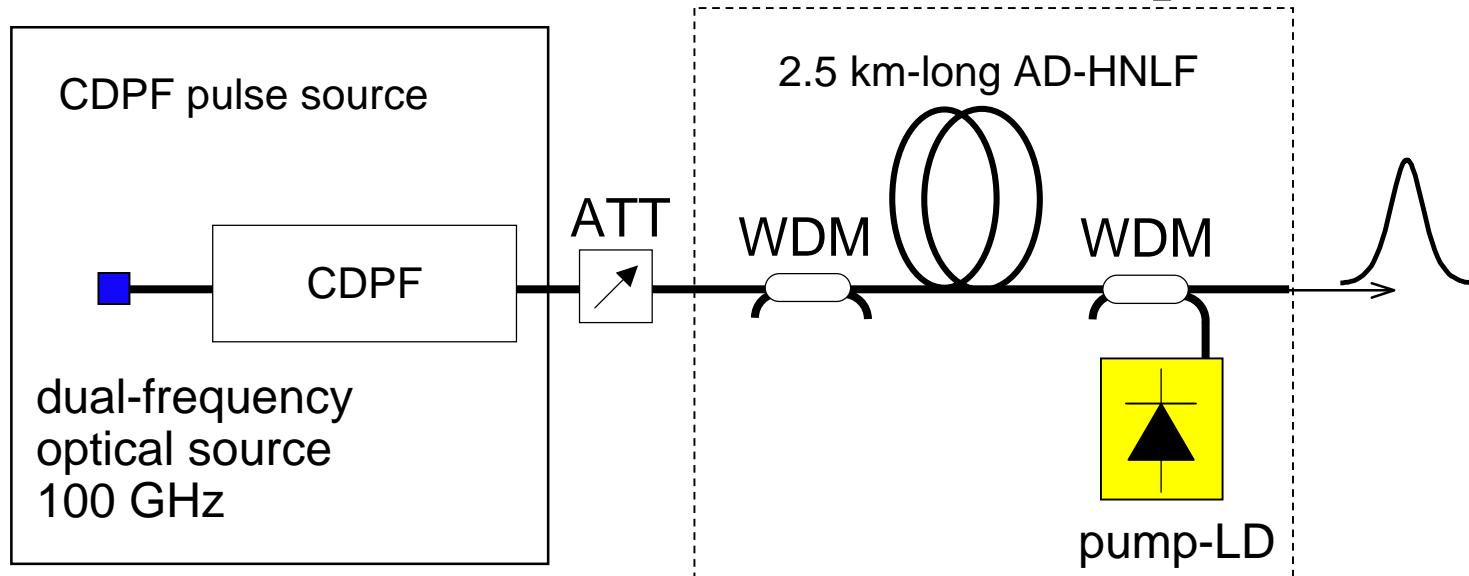
Duration $\Delta t = 1$ ps, $\Delta t \Delta v = 0.34$ (0.311, if TL-soliton)

Good sech² fitting in both time and wavelength domain

OSNR larger than 40 dB

Duration tunable pulse source

- Raman assisted adiabatic soliton compression



Conservation of the soliton order

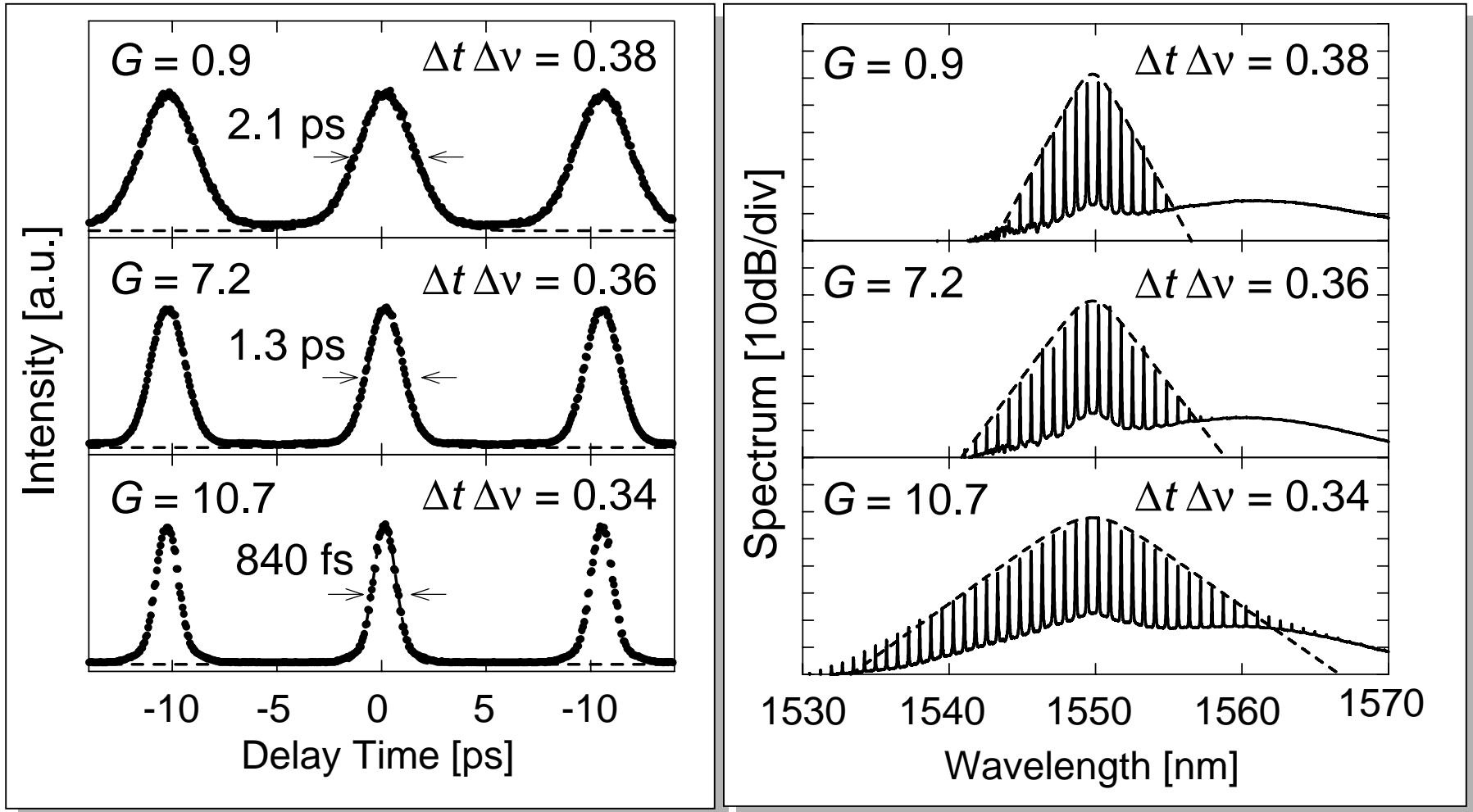
$$N^2 = 1 = \frac{\mathcal{P}_0 T_0^2}{\beta_2} \propto E_p T_0$$

Pulse energy: $E_p \propto P_0 T_0$

large $E_p \rightarrow$ small T_0

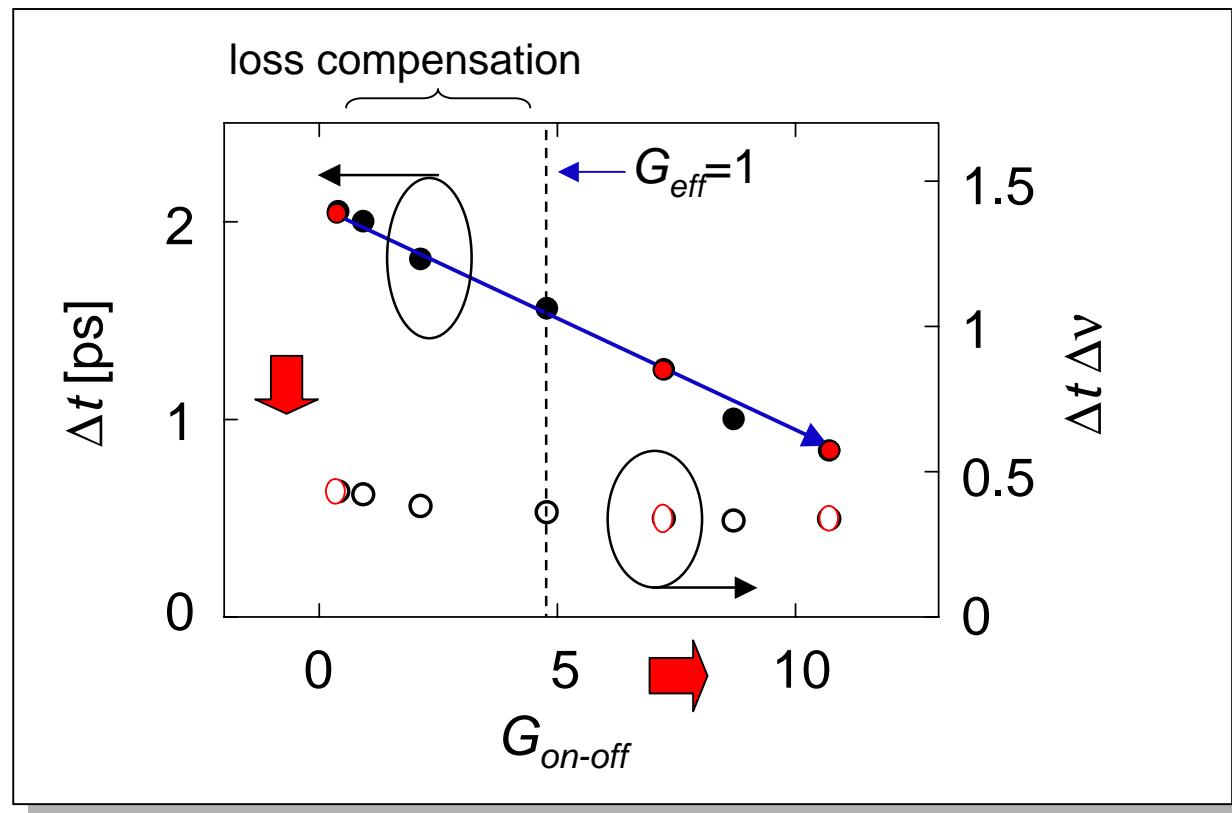
Results

- Autocorrelation traces & spectra: G as on-off gain



Duration tuned by Raman Gain

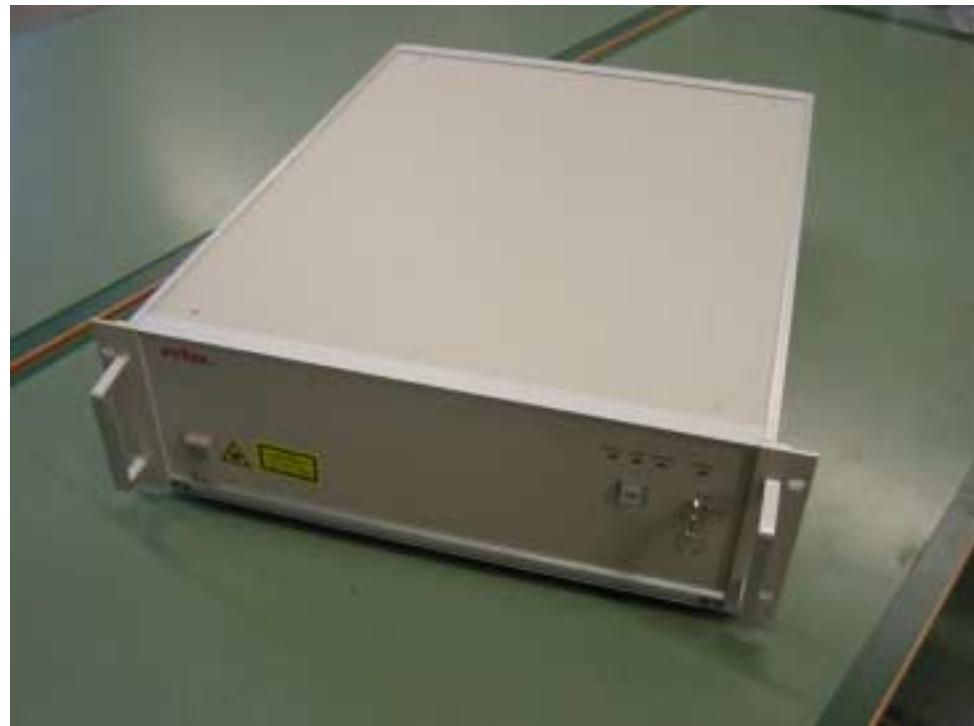
- Time-Bandwidth Product < 0.4



K. Igarashi, *et.al.*, to appear in OFC 2003

Product Image

- Turn-key operation
- Existing telecom components
 - Two CW DFB lasers
 - HNLF
 - Some passive components



430mm(W) × 550mm(L) × 150mm(H)

Summary

- Reviewed the state-of-the-art WDM Pumping
 - Easy flattening of gain and noise
 - Technology evolution of pump laser diodes
 - Co-pumping laser diodes yet ongoing
- Highly nonlinear fibers
 - SiO₂-GeO₂ based HNLF has highest figure of merit
 - High repetition-rate optical pulse source
 - Extremely low noise
 - Tunable pulse duration
 - Ready to go with telecom components
 - Applications to be sought



Thank you!

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Main contributors

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